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EVALUATION OF THE PERFORMANCE CHARACTERISTICS OF BVA RESONATORS--ETC(U)

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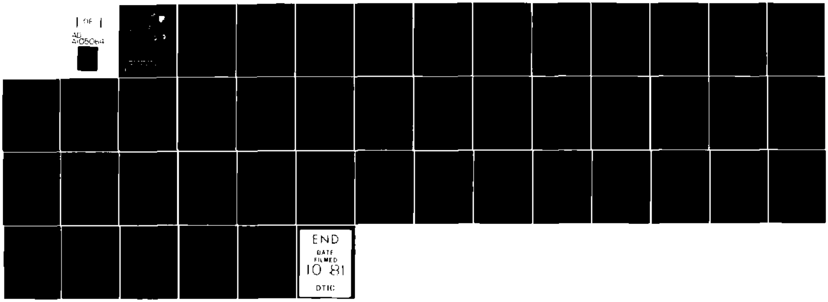

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Final Technical Report
August 1981

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EVALUATION OF THE PERFORMANCE CHARACTERISTICS OF BVA RESONATORS UNDER STATIC AND DYNAMIC CONDITIONS

Frequency and Time Systems, Inc.

Donald A. Emmons

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Laboratory Directors' Fund No. LD0603C1

ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, New York 13441

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This report presents results on evaluation and development of precision oscillators utilizing a novel quartz frequency control element, the BVA resonator. Performance characteristics of the BVA were evaluated utilizing an ensemble of oscillators all having SC-cut BVA resonators. Important results include the demonstration of low g-sensitivity, reduced sensitivity to thermal stress, and very good frequency stability. The systematic dependence of aging rate on crystal drive level was investi-

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gated. A high precision BVA oscillator was delivered to the procuring agency. Throughout the program, technical coordination efforts have involved AFSC, DRET (France) and OSA (SW).

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1.0 INTRODUCTION

This report presents results and conclusions from an evaluation and development study by Frequency and Time Systems, Inc. (FTS) relating to a novel quartz frequency control element, the BVA resonator. The purpose of the study has been to evaluate the performance characteristics of the BVA in conjunction with the development of a deliverable oscillator which makes full use of the new resonator technology. Tasks are outlined in Section 2.0 of the report. An important part of this work has been close cooperation with the originator of the new technology, Dr. R. J. Besson, of Ecole Superieure Nationale de Mechanique et des Microtechniques (ENSMM), Besancon, France. The coordination of activities has involved representatives of the U.S. Air Force Systems Command, Rome Air Development Center (RADC), Hanscom AFB, MA Direction des Recherches Etudes et Techniques (DRET), France, and Oscilloquartz, SA (OSA), Switzerland along with participants from FTS. A joint coordination meeting in Paris in December 1980 has resulted in important understanding of how the military needs in the area of BVA technology can be met. These coordination aspects are discussed in Section 4.0.

The need to establish a performance baseline for advanced BVA resonators led to a concentration of effort to characterize six new resonators representing the prototype industrial design, and to build an ensemble of oscillators. All of these resonators are SC cut quartz and thus exhibit the useful property of thermal stress compensation. Results obtained with this ensemble of oscillators are detailed in Section 5.0, along with measurement techniques and design considerations.

Important results include the demonstration of improved g-sensitivity, in the 10^{-10} per g range (for the worst axis). In addition, the time domain frequency stability at optimum averaging time is typically 3 to 5 x 10^{-13}, and the long term aging is dependent on resonator drive level in a predictable way.

Oscillator S/N 3057 was delivered to RADC in compliance with the contract requirements. Technical data are described in Section 6.0. Although it outwardly resembles oscillator S/N 46 purchased by RADC in 1979, the new oscillator has a number of significant differences:

1) The BVA resonator is a new, smaller design, with improved mechanical mounting of the quartz.

2) The resonator is not a simple retrofit, but is built into the modified FTS 1000 frame at the beginning of construction, with appropriate circuit modification for optimum performance.

3) The oscillator is a member of an ensemble of oscillators, all utilizing fabrication techniques of a pilot production run, providing a measure of the reproducibility and uniformity of the resonator.

The development effort is summarized in Section 7.0, and implications for future development are discussed.

2.0 TASK OBJECTIVES

The overall task objective of this program was the characterization of new BVA quartz resonators developed by Dr. R. J. Besson[1] and produced industrially by Oscilloquartz, S.A. This improved prototype BVA was to be incorporated into a deliverable high- precision oscillator exhibiting improved performance, in one or more performance characteristics, over existing state-of-the-art oscillators. In addition, individual resonators were to be made available to RADC for measurement and testing.

Tasks included the investigation of aging rate, frequency stability, response to environmental perturbations, including dynamic thermal changes, and frequency retrace. These tasks required specific measurement techniques to be defined and implemented.

Results of the measurement program would then be used in understanding potential design trade-offs for the hardware development. Throughout the program, close cooperation would be maintained between FTS and Dr. Besson, and with engineering personnel of OSA. Although it was clear that BVA resonators could provide high stability performance, a number of interrelated resonator construction parameters might require conflicting choices of oscillator design implementation. Some of the interrelated design parameters and desired performance results relevant to this investigation are shown in Figure II-1.

Pursuant to the contract line item requirement, a test plan was submitted on 15 April 1980 which outlined the study and development period to 15 December 1980. This plan showed a breakdown of expected activities covering the following topics:

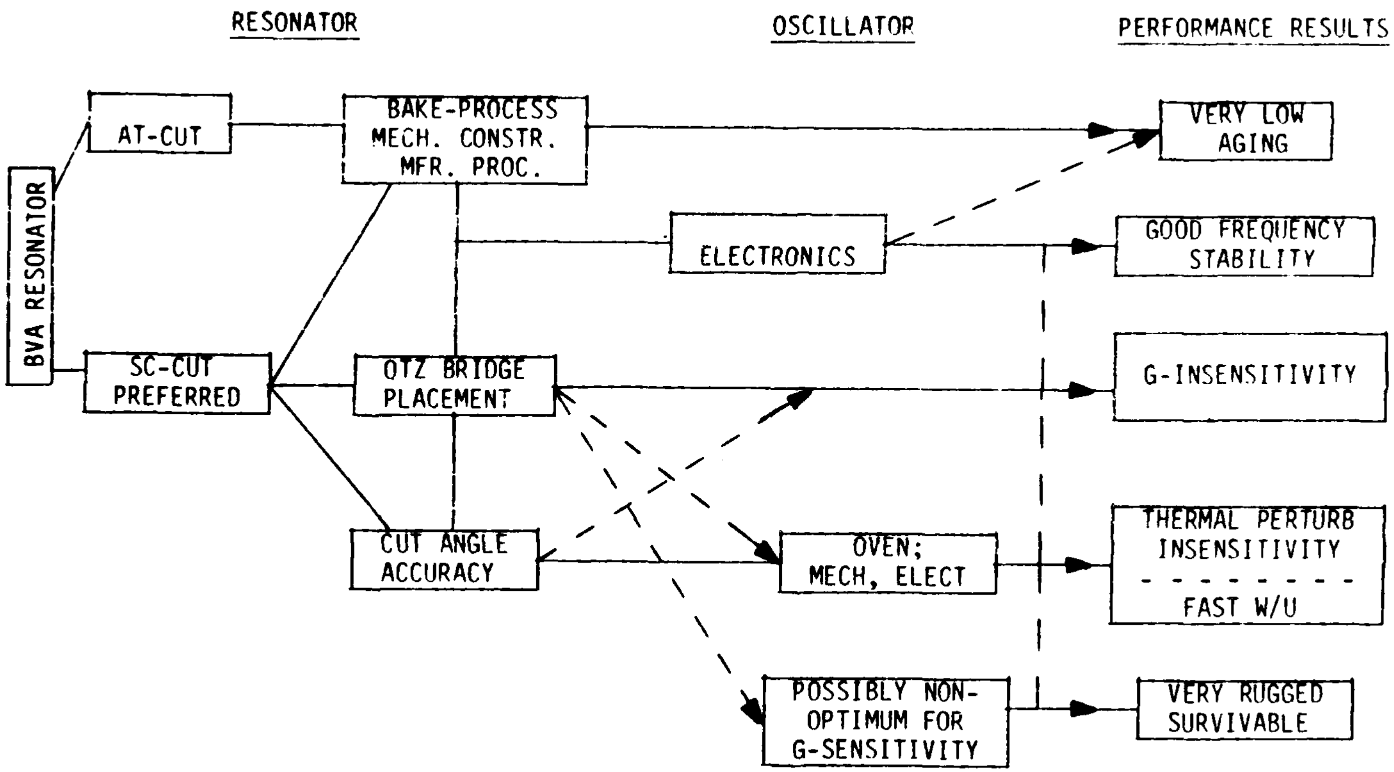

FIGURE II-1 SOME INTERRELATED DESIGN PARAMETERS AND DESIRED PERFORMANCE RESULTS

1) Frequency Stability Measurements
2) Drive Level
3) Warm-Up and Thermal Shock Studies
4) Aging
5) G-sensitivity and Retrace
6) Oscillator Electrical Tests
7) Faster Warm-Up Tests
8) Package Integration
9) Final Performance Tests of Deliverable Oscillator

The technical results and analyses are detailed in sections 5.0 and 6.0 of this report. The finished oscillator, BVA-1000 S/N 3057, was delivered to RADC on 15 December 1980. Individual resonators will be made available to RADC as required.

3.0 METHODOLOGY

3.1 Introduction

This study has centered on the utilization of BVA resonators in practical oscillators. To this end, experimental oscillator test beds have been adapted for BVA use from the FTS 1000 type oscillator, an ovenized unit developed for use with precision overtone resonators at 5 MHz and higher frequencies.

Experimental stability measurements must be done on finished, packaged oscillators in order to minimize spurious perturbing influences. Measurements such as g-sensitivity become possible by reorientation of the oscillator in the earth's gravitational field, without the uncertainty of frequency shift due to changing stray capacitance in a bread-board configuration. It is further necessary to make full use of the inherent frequency stability of the ovenized resonator in order to accurately measure sensitivity coefficients approaching less than 10^{-10} per g.

In the early phases of the study contract, BVA resonators were incorporated into FTS 1000 oscillators by retrofitting. In the final phase, four pre-production oscillators at inception, were modified mechanically to receive new resonators as fully engineered end products. These were then characterized as a part of the program to establish a statistically significant baseline for BVA performance.

The constructional details are described more fully in section 4.0 on the deliverable oscillator.

3.2 Frequency Measurement Techniques

Nearly all of the important characterizations of the oscillators involves measurement of frequency and frequency stability. Measurements can be most conveniently accomplished via the beat period method, against appropriate references.

Figure III-1 shows a block diagram of the measurement system. It consists of a low noise mixer followed by a low pass filter and low noise amplifier. For phase noise measurement, the oscillator under test and the reference source are tuned to the same frequency (zero beat) and the DC feed back signal to an oscillator frequency control input provides for quadrature phase lock. A spectrum analyzer reads the spectral density of phase noise, $S_\phi(f)$.

For frequency measurements, the loop is left open, the reference oscillator is offset from the signal of interest by some low frequency up to say 50 Hz. The offset frequency is then observed at the amplifier output as a very low frequency square wave with precise low-jitter zero crossings. This signal is fed to a high resolution counter having period average capability, permitting measurement accuracy for fractional frequency fluctuations of better than 1×10^{-13}.

In measuring the Allan Variance, successive readings of the average relative frequency (reciprocal period) over a preset time interval can be stored for analysis. In many instances, for example when the averaging time is 100 sec or 1000 sec, it is convenient to store successive period averages on paper tape and then read them into a pre-programmed calculator, along with any relevant aging drift correction, for calculation of the variance.

When absolute frequency is of interest, as for aging measurements, the 5 MHz cesium beam house standard is used as the reference. Long averaging times are used, since short term performance is not relevant for these measurements, and the cesium-controlled source is relatively noisy in short term.

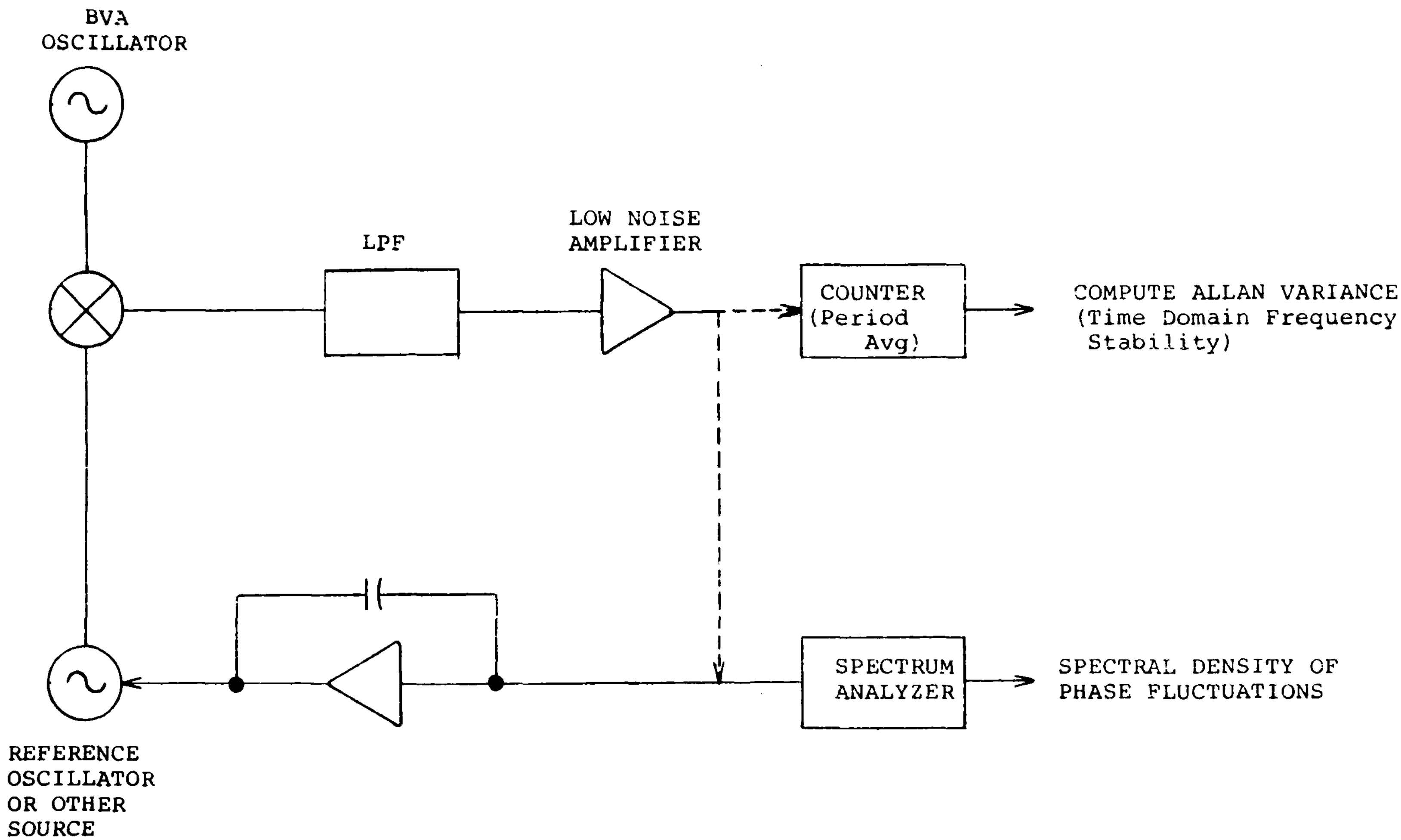

FIGURE III-1 FREQUENCY STABILITY MEASUREMENT SYSTEM

4.0 TECHNICAL COORDINATION

4.1 First Technical Coordination Meeting

The first coordination meeting on BVA resonator development took place at RADC, Hanscom AFB on 26 November 1979. The meeting was devoted to an overview of industrial progress and program objectives. R. Besson of ENSMM presented a review of the concepts which led to his realization of a very high stability electrodeless resonator configuration (BVA) and described the research capabilities of the Ecole Nationale Superieure Mechanique et des Microtechniques (ENSMM).

The status of industrial realization of BVA resonators was described by A. Wavre of OSA. Experimental oscillator results and potential performance capabilities of BVA oscillators were discussed by D. Emmons of FTS.

Program objectives and the organizational structure of DRET were presented by H. Duchaussoy; and N. Yannoni of RADC described the program objectives relevant to the needs of the USAF in the area of tactical oscillator development.

These were followed by general discussion on the prospects for industrial realization of BVA resonators and the need for oscillator development. It was agreed that continuing coordination especially of a bilateral nature would be both necessary and desirable, in view of the number of contributing organizations.

The probability of achieving technically significant results in production quantities was considered to be very high for 5th overtone AT-cut and 3rd overtone SC-cut resonators. Oscilloquartz agreed to a substantial manufacturing engineering effort to reduce the BVA technology to the serial production stage. FTS commited to study, modify and improve its Model 1000 electronics package to

make full use of the performance offered by the BVA resonators and to evaluate resonators to be supplied by OSA and the ENSMM. It was agreed that the ENSMM focus was to be on new developments and basic research studies towards faster warm-up, size reduction, and zero-aging, as well as on scientific support to OSA and FTS.

4.2 Visits and Collaboration

This study and development effort was highlighted by two visits to FTS by Dr. Raymond Besson. In late May, 1980, Dr. Besson spent one week discussing constructional details of the BVA resonators, new solutions to the problem of stress free mounting, and details of oscillator circuitry and instrumentation. Also visiting FTS briefly were E. Graf (Chief Engineer, Electronics) and U. R. Peier (Chief Engineer, Crystal Manufacturing) of OSA. Besson and Peier reported results on the industrial production of BVA resonators at OSA. Ultrasonic machining and final polishing of the quartz was described, as well as final bake, pump-out and sealing of the finished cold-weld cans.

The cooperative interaction between ENSMM, OSA and FTS resulted in the incorporation of BVA resonators into the FTS 1000 type oscillator. An SC cut 3rd overtone unit driven at 265 W showed phase noise floor of $S_\phi(f) = -153$ dB which is limited by the system noise floor. The time domain frequency stability was also shown to be in the low 10^{-13} range, even for relatively high resonator drive level.

In addition, a new oscillator designed at OSA operating with a 5th overtone AT cut BVA crystal gave performance in agreement with the measured loaded Q of 1.5×10^6. This oscillator development gives OSA a useful test-bed for early evaluation of their prototype BVA resonators.

During late May, discussions relating to program coordination made it clear that a sizeable number of resonators of fixed design and identical manufacture was needed for establishing a statistically significant baseline of data on BVA performance. It was agreed that Dr. Besson would return to FTS for an extended visit to take part in measurements when those resonators became available.

This second extended visit was made by Dr. Besson for several weeks in August-September. This permitted a very close cooperation in measuring and characterizing performance of seven new resonators of a prototype nature which went into the ensemble of BVA-1000 oscillators. Because of anomalies in performance, one resonator was excluded from the sample, and used for survival vibration testing. Gravitational force sensitivity was of particular interest for these oscillators, and was found to range down to 1×10^{-10} per g, along the most sensitive axis. The measured worst axis sensitivity was less than 7.5×10^{-10} per g.

4.3 Second Coordination Meeting

A coordination meeting was held on 10 December 1980 in Paris.

5.0 TECHNICAL RESULTS

5.1 Introduction

This section details the technical results of the BVA study and development effort. Particular emphasis is placed on the results from an ensemble of six oscillators (four of which are preproduction BVA-1000 units), which demonstrate systematics and reproducibility of the improved BVA design. This latest design includes improved vacuum feedthrough headers for the cold weld sealed can, and a new kinematic mounting for the quartz resonator, for better immunity from external mechanical perturbation and thermal hysteresis.

An earlier prototype BVA (the first of the SC cut units available to FTS) had been successfully incorporated into an FTS 1000 oscillator(2) and delivered to RADC in 1979 under terms of a purchase order agreement. This oscillator (S/N 46) was returned on loan to FTS early in 1980 for further testing. During that period the frequency stability was measured against a hydrogen maser(3). The best stability occured for averaging times between 20 and 200 sec, and was better than 1.5×10^{-13}.

The unit also demonstrated quite good turn-on characteristics, with a thermal shock transient of a few $\times 10^{-9}$ overshoot when reaching final frequency. Thus the reduced thermal stress property of the SC cut was demonstrated. (The overshoot for AT cut resonators is 20-50 times larger.) In addition, the g-sensitivity coefficient was quite good, in the order of 4×10^{-10} per g.

However, the reproducibility of these performance factors for SC cut 3rd overtone BVA resonators was an unknown quantity.

Additional measurements on both 5th overtone AT cuts and 3rd overtone SC cut resonators, pointed toward the latter as being preferred for further development of a rugged, perturbation-insensitive device. Although the BVA structure intrinsically improves the g-sensitivity performance even of AT cut quartz, the additional improvement for SC-cut is of great importance. Moreover, it is only with the doubly rotated SC that the desired insensitivity to thermal shock can be gained. This has implications also in terms of expected improvement in immunity to ionizing radiation. It is known that at least part of the fast transient response to radiation pulses is associated with the heating effect in the quartz. One of the early motivations for the development of the SC cut was the hope of reduced sensitivity to this effect. Experimental work on both transient and long term frequency offsets induced by ionizing radiation has been done at RADC[4].

It has now been repeatedly demonstrated that the ±15 seconds of arc angle tolerance required for well-behaved SC cut resonators can be easily held in the BVA fabrication techniques. These techniques also realize the potential high Q of the doubly rotated cut, such that $Q = 2.5 \times 10^6$ or more can be achieved even for 3rd overtone resonators.

5.2 New Resonator Characteristics

The electrical characteristics of new SC cut 3rd overtone resonators are shown in Figure V-1. This ensemble of six units, identified by oscillator serial number shows very little spread in the series resistance and Q value. The frequency turnover point (for SC cut quartz, a maximum in the frequency versus temperature characteristics) shows a close grouping about 57°C, chosen for ease of experimentation. For many applications it is necessary to have a higher turnover temperature, with a corresponding change in angle of the cut; as has been demonstrated at ENSMM and OSA.

OSCILLATOR S/N	R_s (Onms)	Q (10^6)	T_o (°C)	G-sensitivity, worst axis (in 10^{-10} per G)
3055	58	2.46	59.5	5
3056	58	2.46	56.5	4
3057	59	2.35	54	7
3058	59	2.45	57	1
3181	73	2.1	55	7.5
3800	63	2.3	57	3.2

FIGURE V-1 SC-CUT THIRD OVERTONE RESONATOR CHARACTERISTICS

Also shown on Figure V-1 are the intrinsic g-sensitivities of these resonators as measured by reorientation of the oscillator in the earth's gravitational field. These values are to be contrasted with the typical conventional resonator (AT) sensitivity of 1 to 2 x 10^{-9} per g. More importantly several of the units show the feasibility of attaining very low numbers, of order 1 x 10^{-10} per g. It is now also established with other resonators that with specific attention to the placement of the quartz bridges in the BVA structure, sensitivity less than 10^{-10} per g can be achieved.

The tabulated g-sensitivities are for the worst axis case, which is typically not co-linear with a principal geometric axis of the resonator nor oscillator chassis. These measurements will be described more fully in the section on g-sensitivity.

5.3 Frequency Stability Results

Time domain frequency stability (Allan Variance) results for various representative averaging time τ are shown in Figure V-2. The first four oscillators, S/N 3055 through S/N 3058 are the preproduction BVA-1000 ensemble described above. The other two oscillators were modified to be quite similar to the BVA-1000 in most electrical and mechanical details.

All measurements are oscillator-pair results, in which the reference oscillator was either another BVA-1000 or a house reference oscillator. Thus these results are an upper bound on the individual oscillator noise at the given averaging time. The measurements were carried out as shown in Figure III-1.

The best results, in the region of 10 to 100 seconds averaging time, are seen to be 3 to 4 x 10^{-13} which is consistent with

Allan Variance $\sigma(\tau)$ in Units 10^{-13}

	τ = 1 sec	10 sec	20 sec	100 sec	
3054		12			
3055		10			
3056	9	5	3		σ(200 sec)=4 σ(2000 sec)=15
3057	5.9	3.4		4.3	
3058	9	5		4.2	
3181	5.9	3.4	4	4.2	
3800	7.5		5		

Figure V-2 FREQUENCY STABILITY RESULTS FOR SC 3rd OVERTONE OSCILLATORS; Pair Measurement Induces Reference Noise

a single-source equivalent noise of better than 2.2×10^{-13}. In addition a few very long term measurements also show good stability results; in particular S/N 3056 shows 1.5×10^{-12} at 2000 seconds averaging time.

Over a wide range of crystal drive level, the short term frequency stability does not appear to depend strongly on drive power. In the frequency domain, measurements of the phase noise $S_\phi(f)$ on several of the units show the effect of high drive level in reducing the phase noise floor (at 1 kHz) from the -140 dB typically seen with conventional plated resonators driven at the 1μW level. For example, S/N 3058, with a resonator drive level of 165μW, exhibits S_ϕ(1 kHz) = -149 dB, and S_ϕ(2 Hz) = -127 dB, measured in a 1 Hz bandwidth. Thus the high drive level has by no means degraded close-in phase noise while improving the white-noise floor.

Oscillator S/N 3181 shows S_ϕ(1 KHz) = -150 dB, at moderately high drive level. The close-in phase noise is characterized by S_ϕ(2 Hz) = -124 dB, and exhibits classical $(f)^{-3}$ behavior.

5.4 Resonator Drive Level - Aging

One of the most important adjustable parameters in the oscillator circuit is the oscillation power level in the resonator. Noise power considerations show that in order to have a phase noise floor of say -160 dB may require on the order of 100μW for a resonator of R_s = 50 ohms. Other considerations may further limit the attainable noise floor, of course.

For the BVA resonators, drive level has an important effect on aging rate as well. The level is determined by:

1) the effective series resistance of the quartz, and the degree of frequency pulling in the circuit,

2) the values of passive circuit elements in the oscillator sustaining stage, and

3) the value of AGC amplifier gain, and thus the required sustaining stage gain (see Figure VI-1).

The basic oscillator circuit is detailed in Figure V-3. The resonator (BVA) operates at series resonance with some effective load capacitance made up of C3 in series with the voltage variable capacitor C_V, along with parallel stray capacitance and C_0 of the crystal. The resonator has a large value resistor across it to ensure zero dc voltage, since the voltage frequency effect is non-vanishing in SC cut crystals.

This oscillation sustaining stage works by emitter feedback, the loop gain being controlled via the current in Q1, set by base bias. That is, increased r.f. amplitude to the AGC amplifier (Figure VI-1) decreases the dc level on the AGC line, which in turn decreases the gain of Q1.

The degree of r.f. amplitude control is a function of the sustainer /AGC amplifier loop gain. Traditionally, for conventional plated resonators in high-stability oscillators, this loop gain is maintained at a high value such that fluctuations in drive level (r.f. amplitude) are held to the order of 10^{-4}. This is necessary because of the large, non-linear dependence of frequency on drive level. One reason why traditional drive levels for 5th overtone plated resonators are kept at about $1\mu W$ is to achieve frequency stabilities better than 10^{-12}.

However, the electrodeless BVA resonators exhibit a much smaller drive level - frequency dependence. In the procedures for setting

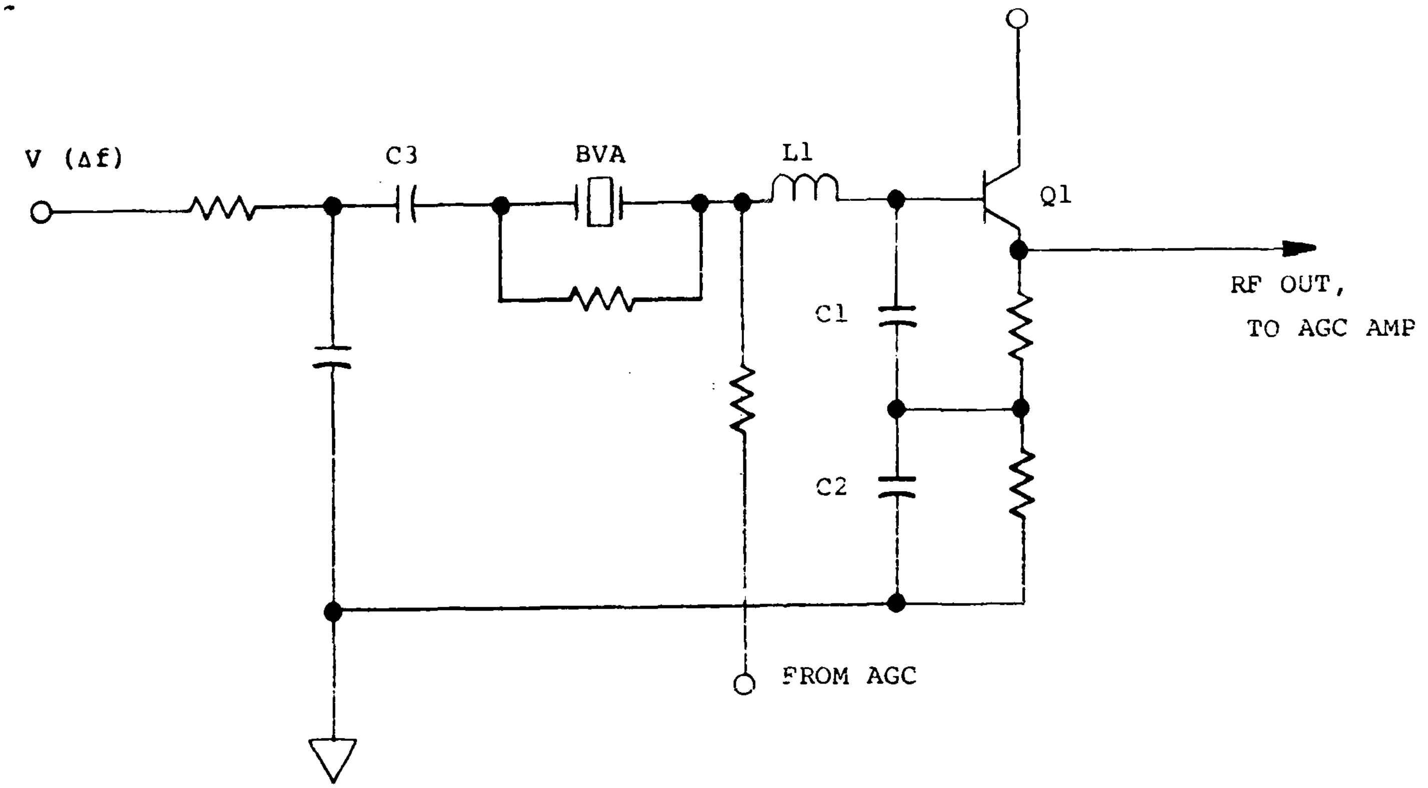

FIGURE V-3 SIMPLIFIED OSCILLATOR SCHEMATIC

resonator drive level to be described, it is typical that the AGC loop gain is a factor of 3 to 10 smaller than for the standard circuit. In spite of this, we consistently see frequency stabilities $\sigma_y(\tau)$ which are in the 10^{-13} range.

Referring again to Figure V-3 the circuit L1: C1: C2 is series resonant at the frequency of interest. The Q of this circuit is high enough to suppress oscillation at the B mode frequency, which is 10% higher than the desired C mode frequency. The circulating current through the resonator is set by the Q1 output r.f. level, by the value of L1, and by the impedance of the resonator.

In measurements of aging versus drive level (see Figure V-4), various drive levels were set by discrete selected values of L1. This differs from the initial work on BVA oscillators in which drive level changes were made by changing the AGC amplifier gain. In the present case, for the ensemble of oscillators, AGC amplifier gain was preset on the production line, at a value which gave a lower limit drive level of 30μW for the typical resonator. Figure V-4 shows results on aging rate versus drive level systematics.

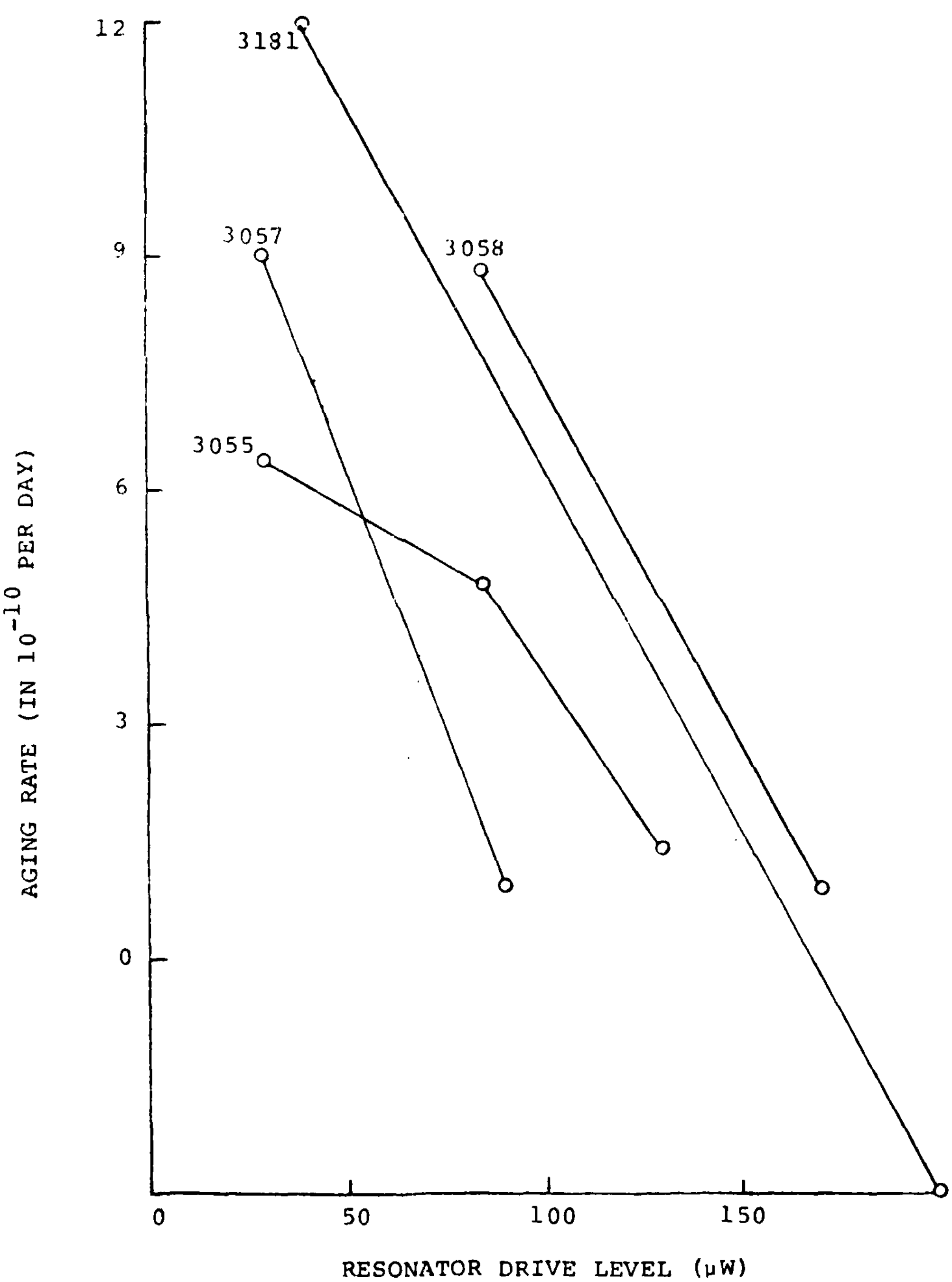

FIGURE V-4 AGING RATE VERSUS DRIVE LEVEL

5.5 Fast Warm-Up and Frequency Retrace

Modified crystal ovens with boosted warm-up power and reduced thermal mass have been used to investigate fast warm-up of BVA resonators. With up to 24W of power at turn-on, operating temperature can be reached in less than 10 minutes.

However, the BVA structure in the present design does not lend itself to rapid heat transfer from the enclosure to the quartz. The resonator itself is deliberately isolated to a high degree from the surroundings for mechanical decoupling of external stress effects. Thus the time for warm-up to operating frequency is still 30-40 minutes even with the rapid warm-up oven.

One SC-cut resonator, of an earlier series, reached frequency maximum 26 minutes after turn-on. The overshoot was approximately 10^{-8} which is an order of magnitude improvement over AT cut. (Successive warm-ups showed a retrace to 1.2×10^{-9} at the 100 minute mark.)

Of the recent ensemble of oscillators, S/N 3800 was also modified temporarily for rapid warm-up (20W; 6 minutes to reach temperature.) In this case, part of the warm-up power was delivered via a heater wrapped directly on the BVA resonator enclosure. The frequency overshoot was of order 10^{-7}. The reason is that when the stress compensation for the SC quartz blank is not exact, then the residual thermal shock effect is magnified, just as for AT cut, by the rate of change of temperature. Wrapping the heater directly on the resonator greatly exaggerated this non-vanishing sensitivity.

However, for most of the ensemble, the SC resonators exhibit good thermal stress compensation as seen by the lack of frequency overshoot during normal warm-up; that is, 15 minutes at 12W to reach operating temperature, and 45 minutes to final frequency with no overshoot worse than 10^{-8}.

This is to be contrasted with the dynamic thermal behavior of AT cut quartz. Measurements were done in the 2nd quarter of this study, utilizing AT cut quartz in a BVA oscillator modified to allow step changes in oven temperature about some equilibrium operating point. The results were consistent with a sensitivity of $\Delta f/f \simeq 10^{-5}$ for a 1°C per second gradient at the resonator enclosure, as reported in the literature[5] for conventional plated resonators.

In view of the conflicting requirements of fast warm-up and mechanical isolation, an experimental development program at the resonator design level must contine. The question of frequency retrace requires further work also. Although several of the resonators show retrace well below the 10^{-9} level, some do not. It is felt that a full characterization of retrace will involve a thorough understanding of all aging mechanisms which operate when the resonator is turned off, and for this there remains a problem of insufficient data.

One specific measurement on S/N 3181 is of interest. In a series of OFF/ON cycles it was found that several 12 hour off periods appeared to condition the resonator so that subsequent 10 hour and 15 hour off periods caused retrace offsets of $\Delta f/f = 3 \times 10^{-10}$, usually positive. Total frequency shift over a 10 day span which included off periods of 2, 10, 15 and 14 hours, was 7×10^{-10}. These measurements were made with reference to the house standard (cesium frequency standard ensemble).

Another related aspect of oscillator warm-up characteristics is the rather rapid approach to short-term stability for BVA oscillators soon after turn-on. For example, S/N 3181 showed $\sigma_y(14 \text{ sec}) = 3.8 \times 10^{-13}$ at 2 hours after turn-on, after having been turned off for a crystal drive level boost to 200μW.

5.6 G-Sensitivity

The g-sensitivity results shown in Figure V-1 are obtained using the beat frequency measurement scheme discussed previously. The oscillator is oriented in the gravitational field until maximum frequency is displayed. The oscillator is then rotated through 180° about a horizontal axis and the display of minimum frequency is verified. It is further checked that these are the absolute maximum and minimum by making small excursions away from the tentative axis along all possible angular reorientation directions. This then establishes the axis of maximum g-sensitivity.

In a plane perpendicular to this axis, the sensitivity is either small or zero depending on the degree of symmetry in the cutting and mounting of the quartz resonator. Results are quite similar to what has been described for 5th overtone plated units, although instead of being close to the resonator disk perpendicular as it is for AT cut quartz, the axis is closer to lying in the plane of the disk. In either case it is not necessarily coincident with a principal axis of the oscillator chasis[6].

The BVA oscillators also exhibit a corollary property. When the oscillator is rotated about any horizontal axis other than the axis of maximum sensitivity, the resultant frequency deviation is a sinusoidal function of rotation angle. This simply means that the vector component of g-force relative to the main axis is producing the expected frequency shift. It follows also that vibrations along the main g-sensitivity axis produce phase-frequency-perturbations related to the g-sensitivity coefficient, and vibrations in the null-plane direction cause little or no shift.

The correlation of phase noise sidebands with frequency and amplitude of vibration was checked using S/N 3058. Over a range of 2 to 10 Hz, along an axis characterized by the static coefficient 5×10^{-11} per g, the phase noise fit the expected $(f)^{-2}$

reasonably well. Scaled up to a 1 g input, the result at 10 Hz was $S_\phi(10\ Hz) = -92$ dB (that is 43 dB worse than when unperturbed).

Finally, the seventh resonator, which had previously been set aside (see Section 4.2) was installed in an oscillator and subjected to random and sine sweep vibration testing, to demonstrate the resonator survivability. Three sine sweeps, to 70 Hz and 15 g maximum were done. In the vertical axis a one minute random test was done at 10 g rms over a spectrum from 20 to 2000 Hz. No loss of output signal was observed following any of the tests.

6.0 TECHNICAL SUMMARY: S/N 3057

6.1 General

The complete oscillator S/N 3057 was delivered to RADC as part of the contract agreement. Final test data and operating characteristics are detailed below.

This oscillator contains a 3rd overtone SC-cut BVA resonator of improved design over previous ones. During the course of oscillator design study, attempts to improve on the modified Pierce oscillator did not lead to improved performance. Because of the relatively high R_S of the 3rd overtone BVA, the basic FTS 1000 circuit is a good match after modification of some circuit parameters. The production of S/N 3057 utilized standard procedures to the extent possible, but with engineering guidance on changes for optimizing performance.

A major modification was the mechanical interface of the BVA crystal and the temperature controlled oven. Five identical ovens were built for the oscillator ensemble. The BVA resonator fits snugly into an aluminum oven receptacle and is held in place with RTV potting. Thus no undue strain is placed on the BVA welded can, but it is not isolated mechanically from the oven. The BVA enclosure is intentionally grounded to the oven assembly.

6.2 Block Diagram

To understand the overall operation, refer to Figure VI-1. The block diagram shows the relation of oscillator sustaining stage, resonator and AGC buffer amplifier, all of which are contained within the temperature controlled oven.

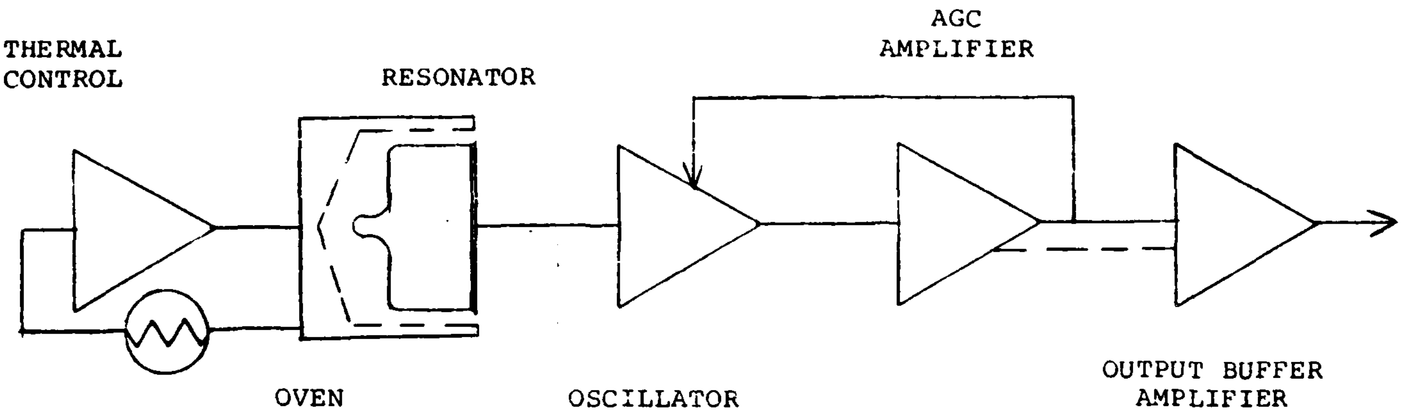

FIGURE VI-1 OSCILLATOR BVA 1000 BLOCK DIAGRAM

The output buffer is actually a dual amplifier, providing two buffered 5 MHz outputs at a level of +13 dBm into 50 ohms. Although these rf outputs have floating shield returns in a specific test set-up, best results may be obtained when the rf connector shells are grounded to the oscillator case or to pin 1 of the mating power connector. The output buffer is outside of the oven.

The operation of the oscillator circuit itself was described in section 5.4. In the case of S/N 3057 the resonator drive level was set at approximately 90μW, because the slope of the aging versus drive level characteristic (see Figure V-3) is steep enough to consider this setting near-optimum.

6.3 Final Test Data

Final test results for the deliverable BVA oscillator, S/N 3057, are shown in Figure VI-2. The resonator has an effective series resistance of 59 ohms, and a measured Q of 2.35 x 10^6. The frequency turn-over point is 54°C which limits the operating ambient temperature to about 46°C. No damage is done if the ambient rises above this temperature for extended periods of time, except that frequency stability will be degraded.

The third-overtone resonator provides a tuning range which is wider than usual for high precision oscillators which have traditionally used 5th-overtone resonators having a smaller "pullability". The tuning range is controlled by the intrinsic motional inductance of the resonator ($L = 4.4$ Hy) along with associated reactive components in the tuning varactor network. The slope of the resonator reactance is given by $dX/df = 4\pi L$ and in this case is 55.5 ohms per Hz. When the external network is changed, the crystal reactance changes to match it, thus pulling the frequency.

	Unit S/N	3057
1)	Resonator	SC cut BVA, 3rd overtone
2)	Drive Level	90 μW, approximately
3)	Output Amplitude	1.0V RMS
4)	Frequency (Nominal)	4,999,976 Hz
5)	Harmonic Distortion	44 dB below rated output
6)	Current Input @ 24V Supply	50 mA typical (room temp) 550 mA Oven warm-up
7)	Frequency Range External $\pm$10V Internal (26 turn pot)	 5 Hz (See Fig. VI-3) 6 Hz
8)	Frequency Stability with Temperature (-28 to +40°C)	 2×10^{-10} (See Fig. VI-4)
9)	Phase Noise, $S_\phi(f)$ NOTE: Often $\mathcal{L}(f)$ is used instead of $S_\phi(f)$; the values would improve by approximately 3 dB in this case.	1.5 Hz; -122 dB 10 Hz; -135 dB 100 Hz; -144 dB 1000 Hz; -147 dB
10)	Short Term Stability (single source, no dead time)	1 sec 4.2×10^{-13} 10 sec 2.4×10^{-13} 100 sec 3.0×10^{-13}
11)	Aging (after 20 days)	$+7 \times 10^{-11}$ per day
12)	G-sensitivity	7×10^{-10} per g, worst axis

FIGURE VI-2 FINAL PERFORMANCE DATA

The frequency tuning is plotted in Figure VI-3. Electrical tuning (EFC voltage applied to pin 2 of the power connector, relative to pin 1, ground) spans 5 Hz for -10V to +10V, and is nearly linear. Mechanical tuning through a 26 turn potentiometer on the front panel provides a total span of about 6 Hz. The two tuning ranges are cumulative.

Frequency stability as a function of ambient temperature is shown in Figure VI-4. The overall temperature coefficient is very small, and is seen to be zero between 20°C and 40°C. An important feature of these measurements is that when ambient temperature is changed abrubtly (say from 20°C to -28°C) the frequency overshoot is less than 2×10^{-11}. The BVA thermal performance thus permits good short term stability even in relatively hostile thermal environments. This is in marked contrast to standard FTS-1000 oscillators in which 10^{-9} is a typical value for the transient overshoot. The overshoot caused by the intrinsic thermal shock characteristic of AT quartz and not by lack of oven temperature control.

Phase noise performance is comparable to that of other oscillators in the ensemble. The close-in performance is particularly good. At 1000 Hz, an additional 3 dB improvement would probably be gained by driving the resonator at twice the power level, as seen for two other oscillators (See section V-C). In that case, however, the aging would go to a large negative value.

The short term Allan Variance results are corrected for the noise of an equivalent reference source. Best performance occurs at approximately 10 seconds averaging time and is 2.4×10^{-13}. This compares favorably with other results obtained on previous prototype BVA resonators.

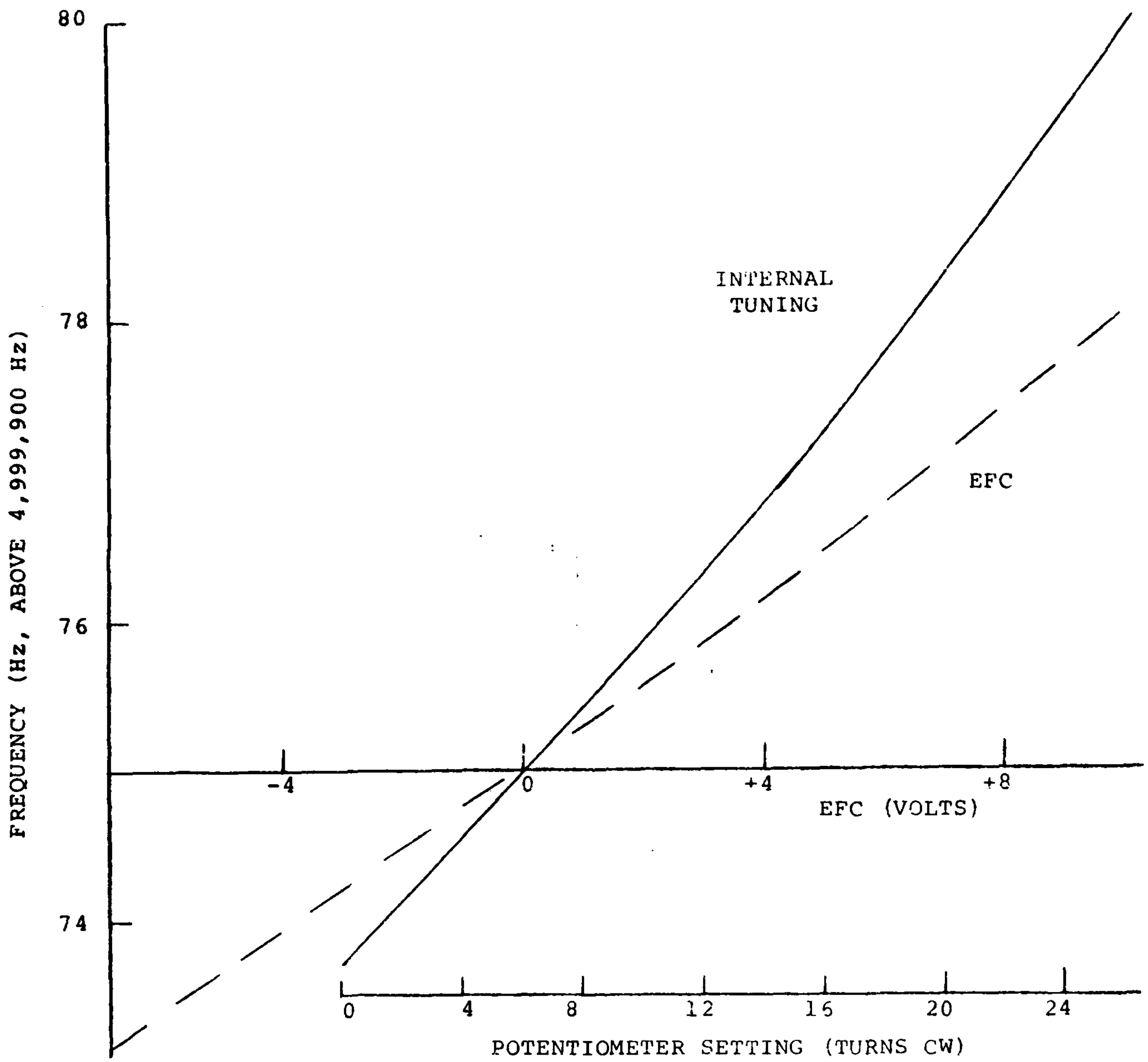

FIGURE VI-3 FREQUENCY TUNING, S/N 3057

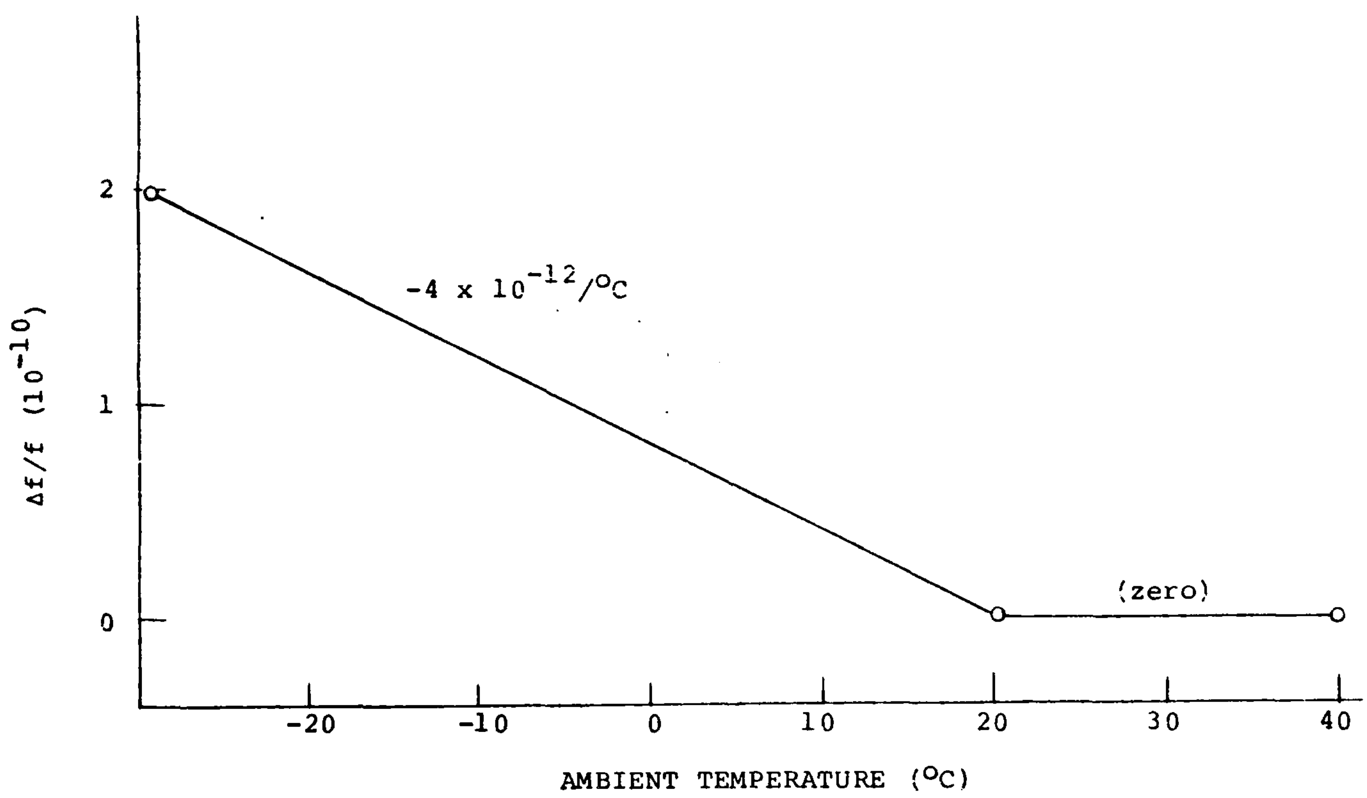

FIGURE VI-4 FREQUENCY STABILITY VS TEMPERATURE; S/N 3057

Measured aging over 20 days of uninterrupted operation toward the end of the test cycle, gave +7 x 10^{-11} per day. Reorientation in the earth's field gives a g-sensitivity of 7 x 10^{-10} per g, along the most sensitive axis. As described in section V-F, the oscillator shows a plane of nearly null sensitivity at right angles to this most sensitive axis.

Typical power drain from the 24V nominal supply is 1.2 - 1.3W at room temperature. Supply voltage may be +22 to 30V and is applied to pin 8 of the 9-pin power connector. Pin 5 is power return.

7.0 SUMMARY AND IMPLICATIONS FOR FUTURE DEVELOPMENT

An ensemble of BVA oscillators has yielded data on the reproducibility of performance characteristics of a prototype group of resonators. Results of this study show that many of the expected benefits are being achieved. Major effort has been concentrated on SC-cut quartz for which the electrodeless BVA technology is particularly suited to realizing maximum performance potential.

Important results include the demonstration of improved g-sensitivity, down to 1×10^{-10} per g. A result of 5×10^{11} per g has been achieved at OSA. Time domain frequency stability for these 3rd overtone resonators is as good as for the best conventional high precision 5th overtone units; parts in 10^{13} are realized which reflects the high Q values (typically 2.4×10^{6}) attained in the quartz fabrication.

Typical resonator drive levels are 100-200μW which allows the realization of reduced oscillator phase noise. In addition, aging rate is a function of drive level, with an optimum low aging drive level of the order of 100μW.

This study and development program has benefitted from the active cooperation of Dr. R. Besson, inventor and developer of the BVA technology, and from interaction with the engineering and manufacturing groups at Oscilloquartz, SA. An important supportive aspect has been the continuing coordination of efforts and objectives between FTS, the USAF, ENSMM, OSA and the DRET.

In technical coordination meetings between representatives of FTS, USAF, DRET, ENSMM and OSA, methods were discussed whereby FTS could establish BVA resonator production for DoD needs if equipment and funds for the required additional specialized capabilities could be made available. Modern clean room facilities and high-reliability manufacturing capability already exist at FTS, along with a fully developed crystal oscillator technology. Cooperation along these lines should continue.

Future work in BVA oscillator development should include realization of a smaller resonator package with more rapid heat transfer to the quartz. Tests at FTS have demonstrated that small thermal shock (small frequency overshoot) is attainable. But, actual warm-up to operating frequency is dominated by the slow thermal transfer from BVA enclosure to the quartz, and thus is still greater than 30 minutes. Improvements addressing this question should be undertaken covering both oscillator oven designs and resonator configuration.

Results of the present work show that BVA technology can simultaneously produce very small thermal shock sensitivity and very low g-sensitivity, a result which may not be possible with conventional plated resonators. However, additional work is needed to ensure that the final design is also rugged and without degradation of other performance characteristics such as frequency stability.

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